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Applications of the infrared thermography in the energy audit of buildings: A review

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ABSTRACT

From a wide range of bibliography (148 publications composed by books, guidelines, scientific papers, and other documents), the study presents a critical review of the use of the infrared thermography (IRT) survey in the building energy audit. After explaining its historical growth, the applicability of passive and active approaches has been described, considering well-established and emerging techniques, general procedures, types of IR-camera used, technical issues, and limitations. The passive approach is the most common to detect thermally significant defects. Thus, a specific procedure for the energy audit has been reported, matching different standards, guidelines, and professional advice. Similarly, recurring energy related problems are toughly presented (i.e. thermal characterization of buildings; thermal bridging, insulation level, air leakage and moisture detection; indoor temperature and U-value measurements; human comfort assessment). Finally, advantages and potential sources of errors as well as future trends in the use of IRT for the energy audit have been described. The research aims to serve as a reference for energy auditors and thermographers, to decide upon the best procedure for detecting specific energy defects.

1. Introduction

The European Commission defines the energy audit as "[…] *a systematic procedure to obtain adequate knowledge of the existing energy consumption profile of a building or group of buildings, of an industrial operation and/or installation of a private or public service, identify and quantify cost-effective energy savings opportunities and report the findings*" [1]. The legislative framework emphasizes its role to identify energy inefficiencies, to reduce energy inputs, and to define potential measures for improving energy efficiency and human comfort [1]. In parallel, the literature attempts to outline a shared methodology for the energy assessment. The first studies concern the building management [2] and the efficiency of lighting and air-conditioning systems [3]. Only later, specific procedures on the whole building have been developed [4–6]. Particularly, Thumann and Jounger [6] theorized three types of building energy audit according to the analytical level to be obtained: (i) "walk-through audit", a visual inspection to evaluate the general energy quality and to individualize inefficiencies and savings potentials during a short-term visit (one-day audit); (ii) "standard audit" to quantify the energy losses linked to a specific problem; and (iii) "simulation audit" based on deep inspections and dynamic simulations of the energy performance. Each level of analysis requires data collection and elaboration of results more and more complex and refined. This theory has been widely replicated, considering also sustainability [7] and engineering approaches [8–11]. Moreover, a shared procedure, as well as the competences of the energy auditors, have been stated at European level [12].

Several Non Destructive Testing (NDT) supports the building energy audit to understand complex fluid dynamics phenomena, to characterize materials and structures, to control the manufacturing processes, and to improve the design and the fabrication of products [13]. Particularly, infrared thermography (IRT) provides very useful information to identify quickly the thermal anomalies related to structural features, building materials, and energy problems [14–16]. It is a contactless test method based on the use of an infrared (IR) imaging system, calibrated for measuring the distribution of the emissive power of surfaces at various temperature ranges [17,18]. The IR-camera produces a sequence of two-dimensional and readable IR-images (thermographs), where specific colors and tones identify differing temperatures [18]. The devices normally operate in the short (3–5 μm) and in the long (7–14 μm) wave IR-bands [18]. Another window is in the near-IR (0.78–3.0 μm). The short wave band is mainly applied for high-temperature inspections (i.e. industrial process and HVAC systems) while the long wave scanners are the most efficient for thermal ranges of 27–65 °C [6,13]. The IRT survey is ever more used for building diagnostics, both for new and existing constructions. Its first applications

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Nomenclature and abbreviations

R	Thermal resistance (or R-value), m^2K/W
U	Thermal transmittance (or U-value), W/m^2K
C	Thermal conductance (or C-value), W/m^2K
λ	Thermal conductivity (or λ-value), W/mK
C_p	Heat capacity, MJ/m^3K
α	Thermal diffusivity, mm^2/s
ρ	Density, kg/m^3
ε	Thermal emissivity on the entire spectrum, –
ν	Wind speed or air velocity, m/s
Φ	Heat flow rate in steady-state conditions, W
T_a	Air temperature, K or °C
T_i	Interior environmental (indoor) temperature
T_e	Exterior environmental (ambient) temperature
ΔT	Difference between indoor and ambient temperatures = (T_i-T_e)
T_s	Surface temperature
T_{sa}	Apparent surface temperature
T_{refl}	Reflected temperature
ΔP	Difference between indoor and outdoor pressure, Pa

in the mid of 1980s regarded civil engineering and preservation of cultural heritage [17,19]. By the early 2000s, it was applied also to electrical and mechanical installations [17]. Then, the International Energy Agency (IEA) stated its importance for detecting energy defects in Annex 40 (2004) [20] and Annex 46 (2010) [21]. In parallel, the development of new restrictive European legislation on the energy efficiency of buildings led to a diffusion of its use also to energy audit [1,22–24]. In the last fifteen years (2002–2017), its applications in buildings considered also thermo-physics, fluid dynamics, energetics analyses [19], passive methodologies [24], smart buildings, and environmental control [25]. Furthermore, IRT is obligatory for selling new and existing houses in several countries (i.e. France, Denmark) [26]. Despite this, an extensive overview of this literature lacks, with the aim of integrating academic and applied studies, standards procedures, future developments of IR-cameras and key devices.

2. Aims and methodology

The paper aims at presenting a critical review of the use of the IRT survey in the building energy audit, updating the studies published in the last fifteen years (2002–2017) on its more general use in building diagnostics [17,19,24,25]. After explaining the historical growth of IRT, its applicability to the energy audit has been described, considering both well-established and emerging approaches, general procedures, types of IR-camera, qualification procedures, technical issues, and limitations. The passive approach results the most common to detect thermally significant defects [24]. Thus, a specific procedure for the energy audit has been reported, matching different standards, guidelines, and professional advice. Similarly, recurring energy related problems are toughly presented, comparing practical and theoretical studies based both on passive and active approaches. Finally, advantages, limitations and potential sources of errors, as well as future trends in the use of IRT for the energy audit, have been described. Fundamentals of IR theory are not treated, because they are extensively explicated in the literature [7,17,19,24,25,27,28]. The research neither means to be exhaustive or definitive, but simply aims to serve as a reference for energy auditors and thermographers to update their knowledge in this field.

The study adopted the same methodology developed by Fox et al. [24] that resulted very rigorous and compete. It is based on two research steps. First, a preliminary literature review using key-words has been conducted to determine the current issues on the use of the IRT in the energy assessments. Key words concerns technologies (e.g. IR-camera), methodologies (e.g. IRT survey, thermographic inspection, thermovision; and so on), approaches (e.g. passive and active thermography, walk-through thermography, pulsed thermography, and so on), recurring problems (e.g. thermal performance, air leakage, moisture, and so on), and standards (e.g. ASTM, RESNET, and ISO). Then, bibliographies and references suggested by the literature have been followed up for a deeper investigation on specific topics. In total 148 literature sources have been analyzed spanning from the last fifty-five years (1962–2017). Literature was divided in: (i) "academic studies" to find scientific interest and theoretical approaches (i.e. books, academic journals, conference papers); (ii) "grey studies" [24] to discover technical advice and practical methodologies (i.e. standards, professional guides, technical reports, and governmental guidance notes); and (iii) "professional works" to look for new products and innovative approaches (i.e. commercial web pages of products or IRT associations).

3. A brief history of infrared thermography

IRT has a long history, although its use has increased dramatically with the commercial and industrial applications of the past fifty years. Sir William Herschel discovered the existence of a portion of the electromagnetic spectrum ("thermometrical spectrum") in 1800, looking for optical filters to reduce the brightness of the sun in telescopes during solar observations [24,27–29]. Several years later (1835), Macedonio Melloni developed the first detector based on this type of radiation ("thermopile IR detector"), opening the studies on the IR-band [19,27,29,30]. John Herschel, the Herschel's son, settled out the first thermograph utilizing the differential evaporation of a thin-film of an oil exposed to the heat patterns (1840) [24,28]. In parallel, Samuel Pierpont Langley discovered the bolometer in 1880 (the "Langley's bolometer"), a material that changes its electrical resistance with temperature ranges [27,31]. This finding permitted the examination of the far solar irradiance into the IR region and the measurement of the solar radiation intensity at various wavelengths, enabling significant improvements in the sensitivity of the IR rays detection [29,31,32]. This bolometer followed continuous advances over than 20 years and it is considered on the basis of the modern IR-cameras [31]. Between 1870 and 1920, the first quantum detector based on the interaction between these radiations was developed, transforming definitively the nature of the detection for the considerable reduction of the response time and the increasing of the measurement accuracy [29]. The thermal imaging cameras were established in the military sector on the basis of this quantum detector. In 1929 Kálmán Tihanyi invented the first IR-sensitive camera for anti-aircraft defense [31]. Important progress on photo sensors and image converters was made between the two World Wars, showing the importance of this technology for the night vision of military objects (missiles and so on) [30]. Significant was the introduction of several IR detectors from the bolometer between 1930 and 1960, such as lead sulphide (PbS) (range 1.5–3 μm), indium antimonide (InSb) (range 3–5 μm), and mercury – cadmium – tellurium (HgTeCd) (range 8–14 μm) [30,33,34]. They worked with on optical-mechanical scan systems and required a cryogenic cooling [30]. In the late 1950s, Texas Instruments, Honeywell and US Military settled out a single-element detector for producing IR-images [28]. The high cost of this technology forced its application mainly for military proposes also in the following decades (1950–1965) [29]. In parallel, some studies demonstrated its utility for visualizing the early stages of breast cancer, because the tumor cells would draw more blood creating a hot spot in the IR-image (1950–1960) [35]. Barnes-Agema in the late 1960s sold the first commercial real-time IR-camera (1966) that required cooling with materials such as liquid nitrogen and compressed gas